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High-Diversity Bandwidth-Efficient Space-Time Block Coded Differential Spatial Modulation

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ABSTRACT By choosing indexes of antennas, differential spatial modulation (DSM) transmits additional data bits without increasing power consumption, radio-frequency circuits, and pilot overhead. Space-time block coded DSM (STBC-DSM) is a DSM scheme combined with STBC to enhance diversity. In our earlier work, we propose a bandwidth-efficient STBC-DSM (BE-STBC-DSM) scheme, which interleaves the transmitted symbols. However, the transmit diversity order of existing STBC-DSM schemes is only two. In this paper, we propose an STBC-DSM scheme whose transmit diversity order is four, called high-diversity BE-STBC-DSM (HD-BE-STBC-DSM), by replacing the 2×2 STBC with a full-diversity 4×4 STBC in BE-STBC-DSM. Because the interleaving patterns in the original BE-STBC-DSM cannot be utilized in HD-BE-STBC-DSM, we need to find new interleaving patterns for HD-BE-STBC-DSM. We propose a novel interleaving type, intra-block interleaving, and propose a new design method that differs from the BE-STBC-DSM method. In addition, we propose inter-block interleaving and search patterns of inter-block interleaving. Compared with other DSM schemes with the same diversity order, HD-BE-STBC-DSM is much more spectrally efficient. In addition, HD-BE-STBC-DSM offers the best error performance at high signal-to-noise ratios among all STBC-DSM schemes.

INDEX TERMS Differential spatial modulation, diversity, space-time block code.

I. INTRODUCTION

Spatial modulation (SM) is a multi-antenna technique that uses one transmit antenna each time [1], [2]. By choosing indexes of antennas, SM can send additional data bits without increasing power consumption and radio-frequency circuits. Differential SM (DSM) is a noncoherent SM technique that avoids the pilot overhead and channel estimation [3], [4]. DSM is extended to generalized DSM (GDSM), where more than one but not all transmit antennas are activated at a time. Suppose all transmitted symbols in GDSM are uncoded data symbols, similar to the case of noncoherent two-phase two-way relaying with decode and forward [5]. In that case, the error performance of GDSM is unsatisfactory.

The transmit diversity order of DSM is only one, which results in unsatisfactory error performance. A GDSM scheme that uses Alamouti's space-time block code (STBC) [6], called space-time block coded DSM (STBC-DSM), was proposed in [7] to improve diversity. In addition to the original detector in [7], two new detectors for STBC-DSM were proposed in [8] and [9]. The STBC-DSM scheme in [7] permutates STBC blocks only to ensure that exactly two antennas are activated each time. Because there are only a few possible permutations of STBC blocks, the transmission rate of the scheme in [7] is low. In our recent paper [10], we proposed a bandwidth-efficient STBC-DSM (BE-STBC-DSM)[1] scheme which interleaves the transmitted symbols. By selecting different interleaving patterns, the scheme in [10] is more spectrally efficient than the system in [7].

[1] In [10], to emphasize that it meets the restriction of GDSM, it was called BE-GDSM.

Other coded DSM schemes for increasing transmit diversity have been proposed in [12], [13], [14], [15]. However, DSM whose transmit diversity order is four for $N_T = 8$ or 12 can only be found in [12].

Space-time block coded rectangular differential spatial modulation (STBC-RDSM) [16] is another DSM scheme that uses Alamouti's STBC to increase diversity. Compared with conventional DSM, STBC-RDSM and rectangular differential spatial modulation (RDSM) [17] use fewer time slots so that spectral efficiency is improved. Because the reference block does not have enough information of channel coefficients, two-block differential detection [18], which is utilized in DSM and STBC-DSM, cannot be used for RDSM and STBC-RDSM. For RDSM and STBC-RDSM, only recursive decision-feedback differential detection, which uses all previously received blocks with a forgetting factor, can be used.

Both STBC-DSM schemes in [7] and [10] utilize Alamouti's 2×2 STBC, so the transmit diversity order is two only. In this paper, in order to obtain STBC-DSM whose transmit diversity order is four, we propose replacing Alamouti's STBC with a full-diversity 4×4 STBC [19]. The proposed scheme is called high-diversity BE-STBC-DSM (HD-BE-STBC-DSM). Because the interleaving patterns in [10] are proposed for Alamouti's STBC and thus cannot be used for HD-BE-STBC-DSM, we propose new interleaving patterns, including two types: intra-block interleaving and inter-block interleaving patterns.

Intra-block interleaving is the interleaving within an STBC block, and the transmit diversity order between any two different intra-block interleaving patterns is two. In our design, any two different sequences of data bits correspond to two STBC blocks with different intra-block interleaving patterns, so the transmit diversity order of the whole block of STBC-DSM is four. The idea and the design principle of intra-block interleaving are different from those of the original interleaving in BE-STBC-DSM, so we propose a new design method that utilizes a short linear block code. On the other hand, inter-block interleaving is the interleaving of the symbols of all STBC blocks. In this paper, intra-block interleaving patterns are designed, and inter-block interleaving patterns for eight and twelve transmit antennas are searched.

The spectral efficiency of HD-BE-STBC-DSM is significantly higher than existing DSM schemes with four transmit diversity orders. In addition, computer simulation results show that HD-BE-STBC-DSM provides better error performance at high signal-to-noise ratios than STBC-DSM without interleaving.

Note that the design of interleaving patterns is only related to the number of activated antennas, which means that the proposed patterns can be applied to another full-diversity 4×4 STBC. For STBC with different sizes, such as 8×8 STBC, the proposed interleaving patterns cannot be used, but the proposed idea can be applied to the design and search methods.

The rest of the paper is organized as follows. In Section II, we first introduce the STBC-DSM schemes in [7], modified by using the 4×4 STBC instead of Alamouti's STBC, and then propose HD-BE-STBC-DSM. Subsequently, intra-block and inter-block interleaving patterns for HD-BE-STBC-DSM are proposed in Sections III and IV, respectively. After that, the receiver and simulation results that compare the error performance of STBC-DSM schemes are shown in Section V. Finally, the conclusion is given in Section VI.

Notation: $\|.\|$ denotes the Frobenius norm of a matrix. x^* denotes the complex conjugate of x. diag$\{.\}$ represents the operation from a row vector to a diagonal matrix. $\mathbf{I}_n$ and $\mathbf{0}_n$ denote the $n \times n$ identity matrix and the $n \times n$ null matrix, respectively. $\lfloor \rfloor$ and $\lfloor x \rfloor_{2^p}$ denote the floor function and the largest integer which is a power of 2 less than or equal to x, respectively. $\mathcal{CN}(0, \sigma^2)$ denotes the zero-mean, σ^2-variance, complex Gaussian distribution.

II. HIGH-DIVERSITY STBC-DSM SCHEMES

A. CHANNEL MODEL AND HIGH-DIVERSITY STBC-DSM WITHOUT INTERLEAVING

In the considered communication system, there are N_T transmit antennas and N_R receive antennas, and the channels between antenna pairs are Rayleigh fading and independent of each other. Each block of STBC-DSM contains N_T time slots, and for the tth STBC-DSM block, the transmitted signals are represented by an $N_T \times N_T$ matrix $\mathbf{S}(t)$ where different columns denote different time slots. The $N_R \times N_T$ matrix of the received signals for the tth STBC-DSM block is

$$\mathbf{Y}(t) = \mathbf{H}(t)\mathbf{S}(t) + \mathbf{N}(t) \tag{1}$$

where $\mathbf{H}(t)$ is the $N_R \times N_T$ matrix of channel coefficients whose entries are $\mathcal{CN}(0,1)$, and $\mathbf{N}(t)$ is the $N_R \times N_T$ matrix of AWGN with $\mathcal{CN}(0, N_0)$ entries. At each time slot, k $(1 < k < N_T)$ transmit antennas are activated, i.e., there are k nonzero entries in each column of $\mathbf{S}(t)$.

DSM and STBC-DSM are special cases of differential space-time modulation (DSTM) [18], so the encoding and decoding of STBC-DSM are identical to those of DSTM except for more restrictions on the data matrix. First, data bits are mapped to the $N_T \times N_T$ data matrix $\mathbf{X}(t)$. the transmitted matrix $\mathbf{S}(t) = \tilde{\mathbf{S}}(t)$ is the output of differential encoding, which is

$$\tilde{\mathbf{S}}(t) = \tilde{\mathbf{S}}(t-1)\mathbf{X}(t). \tag{2}$$

The noncoherent ML detection is

$$\hat{\mathbf{X}}(t) = \arg\min_{\mathbf{X}} \|\mathbf{Y}(t) - \mathbf{Y}(t-1)\mathbf{X}\|^2. \tag{3}$$

With the modification of replacing Alamouti's 2×2 STBC with the 4×4 STBC, the STBC-DSM schemes in [7] are briefly described as follows. For $N_T = 8, 12, \ldots,$, the data matrix is

$$\mathbf{X}(t) = \text{diag}\{X_1(t), X_2(t), \ldots, X_{N_T/4}(t)\}\mathbf{A}(t) \tag{4}$$

where $X_1(t), X_2(t), \ldots, X_{N_T/4}(t) \in \mathcal{X}$, which denotes the set of the 4×4 STBC $\begin{pmatrix} x_1 & -x_2^* & x_3^* & 0 \\ x_2 & x_1^* & 0 & x_3^* \\ x_3 & 0 & -x_1^* & -x_2^* \\ 0 & x_3 & x_2 & -x_1 \end{pmatrix}$ [19] in which x_1, x_2 and x_3 are data symbols in $\mathcal{S} = \{1, \exp(j\frac{2\pi}{M}), \exp(j\frac{4\pi}{M}), \ldots, \exp(j\frac{2(M-1)\pi}{M})\}$. Consequently, there are M^3 elements in $\mathcal{X}$. The antenna-selection matrices $\mathbf{A}(t) \in \mathcal{A} = \{\mathbf{A}_1, \mathbf{A}_2, \ldots, \mathbf{A}_Q\}$ is composed of $\mathbf{I}_4$ and $\mathbf{0}_4$. There is only one $\mathbf{I}_4$ in each four rows and four columns, so the number of permutating $\mathbf{I}_4$ and $\mathbf{0}_4$ in $\mathbf{A}(t)$ is only $(N_T/4)!$, which means $Q = \lfloor (N_T/4)! \rfloor_{2^p}$ is small. Hence, the spectral efficiency is $\frac{3}{4}\log_2 M + \frac{1}{4}\lfloor \log_2(N_T/4)! \rfloor$ bits/sec/Hz. For $N_T = 8$, only one data bit determines $\mathbf{A}(t)$ because there are only $\mathbf{A}_0 = \begin{pmatrix} \mathbf{I}_4 & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_4 \end{pmatrix}$ and $\mathbf{A}_1 = \begin{pmatrix} \mathbf{0} & \mathbf{I}_4 \\ \mathbf{I}_4 & \mathbf{0} \end{pmatrix}$ in $\mathcal{A}$.

By such $\mathbf{A}(t)$, the matrices $X_1(t), X_2(t), \ldots, X_{N_T/4}(t)$ in $\mathbf{X}(t)$ do not split apart so $\mathbf{S}(t)$ meets the requirements of GDSM after differential encoding, i.e., exactly $k = 3$ transmit antennas are activated. In the scheme in [20], the entries in $\mathbf{A}(t)$ are 1 and 0 so the value of Q is relatively large. However, $X_1(t), X_2(t), \ldots,$ in $\mathbf{X}(t)$ are likely to split apart, and after differential encoding, the transmitted block $\mathbf{S}(t)$ may activate all antennas. Detailed analysis can be found in [7].

B. HD-BE-STBC-DSM

For HD-BE-STBC-DSM, the transmitted signal is

$$\mathbf{S}(t) = \tilde{\mathbf{S}}(t)\mathbf{C}(t) \tag{5}$$

where $\mathbf{C}(t)$ is the $N_T \times N_T$ column-interchanging matrix consisting of 0 and 1 where there is only a 1 in each column and row. By selecting different patterns of $\mathbf{C}(t)$, additional data bits can be transmitted. The interleaving pattern is $\boldsymbol{\pi}(t) = (\pi^{(1)}, \pi^{(2)}, \ldots, \pi^{(N_T)})$ where $\pi^{(k)}$ denotes the position of the only nonzero entry in the k-th column of $\mathbf{C}(t)$ for $k \in \{1, 2, \ldots, N_T\}$. After the permutation in (5), the kth column of $\mathbf{S}(t)$ is the $\pi^{(k)}$th column of $\tilde{\mathbf{S}}(t)$ where $k \in \{1, 2, \ldots, N_T\}$.

The interleaving patterns in [10] are not valid for the 4×4 STBC. To be spectrally efficient, interleaving patterns that keep transmit diversity order four should be as many as possible. For HD-BE-STBC-DSM, we propose two interleaving types, intra-block interleaving and inter-block interleaving. The interleaving pattern $\boldsymbol{\pi}(t)$ is determined by an intra-block interleaving pattern and an inter-block interleaving pattern. Permutating the entries of an inter-block interleaving pattern according to an intra-block interleaving pattern results in the corresponding interleaving pattern $\boldsymbol{\pi}(t)$. Take $N_T = 8$ as an example. For an intra-block interleaving pattern $\boldsymbol{\pi}' = (\pi'^{(1)}, \pi'^{(2)}, \pi'^{(3)}, \pi'^{(4)})$, the entries $1 + n$, $2 + n$, $3 + n$, and $4 + n$ of an inter-block interleaving pattern become $\pi'^{(1)} + n$, $\pi'^{(2)} + n$, $\pi'^{(3)} + n$, and $\pi'^{(4)} + n$ of $\boldsymbol{\pi}(t)$, respectively, where $n = 1$ or 4. For instance, if the inter-block interleaving pattern is $(1, 2, 3, 8, 4, 5, 6, 7)$ and the intra-block interleaving pattern $\boldsymbol{\pi}'$ is $(1, 3, 4, 2)$, the interleaving pattern $\boldsymbol{\pi}(t)$ is $(1, 3, 4, 6, 2, 5, 7, 8)$.

Define $\mathbf{X}'(t) = \mathbf{C}^{-1}(t-1)\mathbf{X}(t)\mathbf{C}(t)$, and let $\{\mathbf{X}'_1, \mathbf{X}'_2, , \ldots, \mathbf{X}'_n\}$ denote the set of all possible matrices of $\mathbf{X}'(t)$. Define $\mathbf{D}_{ij} = (\mathbf{X}'_i - \mathbf{X}'_j)(\mathbf{X}'_i - \mathbf{X}'_j)^\dagger$ and r_{ij} denotes its rank. As the derivation in [7], the pairwise error probability is

$$P_r\{\mathbf{X}'_i \to \mathbf{X}'_j\} = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \prod_{k=1}^{r_{ij}} \left(1 + \frac{\lambda_{ijk}}{8N_0 \sin^2\phi}\right)^{-N_R} d\phi \tag{6}$$

where $\lambda_{ij1}, \ldots, \lambda_{ijN_T}$ are the eigenvalues of $\mathbf{D}_{ij}$. Therefore, the average bit error probability is upper bounded by the union bound

$$P_b \leq \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1, j\neq i}^{n} B_{ij} P_r\{\mathbf{X}'_i \to \mathbf{X}'_j\} \tag{7}$$

where the error coefficient B_{ij} is the ratio of the number of different data bits between $\mathbf{X}'_i$ and $\mathbf{X}'_j$ to the number of total data bits. The transmit diversity order, denoted by $r_{\min}$, is the minimum value of r_{ij}, i.e., $r_{\min} = \min_{1 \leq i < j \leq n} r_{ij}$.

An equivalent approach of the transmitter of HD-BE-STBC-DSM, which avoids the matrix multiplication in (2), is described as follows. Figure 1 shows the block diagram of the transmitter. There are two types of permutations that carry antenna data bits: one is block-wise transmission order of DSTM (differential space-time modulation) [18] denoted by $\mathbf{p}(t) \in \mathcal{P} = \{\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_Q\}$ and the other is interleaving patterns on DSTM denoted by $\boldsymbol{\pi}(t) \in \Pi = \{\boldsymbol{\pi}_1, \boldsymbol{\pi}_2, \ldots, \boldsymbol{\pi}_R\}$ where $Q = (N_T/4)!$ and R denote the number of elements in $\mathcal{P}$ and Π, respectively. For $q \in \{1, 2, \ldots, Q\}$, $\mathbf{p}_q$ is $(p_q^{(1)}, p_q^{(2)}, \ldots, p_q^{(N_T/4)})$ where $p_q^{(k)} \in \{1, 2, \ldots, N_T/4\}$ $(k \in \{1, 2, \ldots, N_T/4\})$ represents the position of $\mathbf{I}_4$ in the $4k-3$th, $4k-2$th, $4k-1$th and $4k$th columns of $\mathbf{A}_q$.

For the tth STBC-DSM block, input data bits are divided into two parts: one selects $\mathbf{p}(t)$ and $\boldsymbol{\pi}(t)$, and the other is mapped to $X_1(t), X_2(t), \ldots, X_{N_T/4}(t)$. Then $X_1(t), X_2(t), \ldots, X_{N_T/4}(t)$ are differentially encoded independently by

$$S_k^t = S_k(t-1)X_k(t) \tag{8}$$

where $k \in \{1, 2, \ldots, N_T/4\}$. According to $\mathbf{p}(t) = \{p^{(1)}, p^{(2)}, \ldots, p^{(N_T/4)}\}$, S_1^t, S_2^t, $\ldots$, $S_{N_T/4}^t$ are permutated by $S_k(t) = S_{p^{(k)}}^t$ for $k \in \{1, 2, \ldots, N_T/4\}$, and then $S_1(t), S_2(t), \ldots, S_{N_T/4}(t)$ are sent into the symbol-interleaver.

Representing $S_k(t)$ by $S_k(t) = (\mathbf{s}_{4k-3}^t, \mathbf{s}_{4k-2}^t, \mathbf{s}_{4k-1}^t, \mathbf{s}_{4k}^t)$ for $k \in \{1, 2, \ldots, N_T/4\}$, the symbol interleaver interleaves $\mathbf{s}_1^t, \mathbf{s}_2^t, \ldots, \mathbf{s}_{N_T}^t$ according to $\boldsymbol{\pi}(t) = (\pi^{(1)}, \pi^{(2)}, \ldots, \pi^{(N_T)})$. The output of the interleaver is the transmitted signals $\mathbf{S}(t) = (\mathbf{s}_1(t), \mathbf{s}_2(t), \ldots, \mathbf{s}_{N_T}(t))$ satisfying $\mathbf{s}_k(t) = \mathbf{s}_{\pi^{(k)}}^t$ for $k \in \{1, 2, \ldots, N_T\}$.

Differential encoding (2) is equivalent to permutating block-wise transmission order $\mathbf{p}(t)$, and selecting $\mathbf{A}(t)$ is equivalent to choosing $\mathbf{p}(t)$. In other words, if there is not the symbol interleaver, HD-BE-STBC-DSM is equivalent

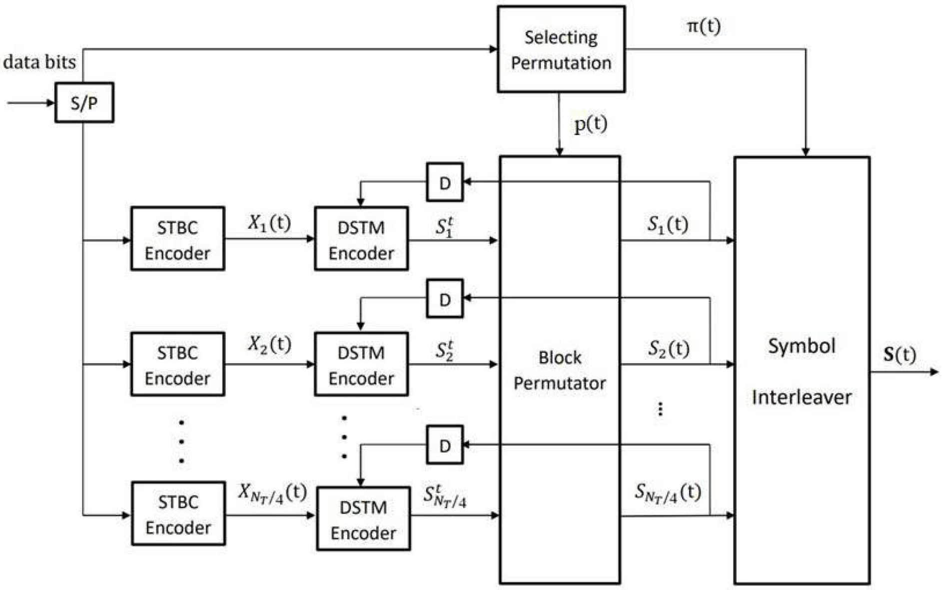

FIGURE 1. Block diagram of HD-BE-STBC-DSM.

to the system in [7] using the 4 × 4 STBC. Compared with [7], additional data bits can be transmitted by selecting different interleaving patterns $\boldsymbol{\pi}(t)$. The spectral efficiency is $\frac{3}{4}\log_2 M + \frac{1}{4}\lfloor \log_2 QR \rfloor$ bits/sec/Hz. Nevertheless, both the transmitter and receiver need to know the set of used interleaving patterns, and the use of interleaving patterns introduces additional complexity.

III. DESIGN OF INTRA-BLOCK INTERLEAVING PATTERNS

Intra-block interleaving interleaves four symbols within an STBC block and maintains transmit diversity order two. Doing such interleaving in two STBC blocks simultaneously can achieve transmit diversity order four. We use the case of $N_T = 8$ to explain. There are two possible forms of $\mathbf{X}(t)$: $\mathbf{X}_0 = \begin{pmatrix} X_1(t) & \mathbf{0} \\ \mathbf{0} & X_2(t) \end{pmatrix}$ and $\mathbf{X}_1 = \begin{pmatrix} \mathbf{0} & X_1(t) \\ X_2(t) & \mathbf{0} \end{pmatrix}$. Let $X_k'(t)$ denote the matrix obtained by switching columns of $X_k(t)$ where $k = 1$ or 2, and define $\mathbf{X}_2 = \begin{pmatrix} X_1'(t) & \mathbf{0} \\ \mathbf{0} & X_2'(t) \end{pmatrix}$ and $\mathbf{X}_3 = \begin{pmatrix} \mathbf{0} & X_1'(t) \\ X_2'(t) & \mathbf{0} \end{pmatrix}$. If the diversity order between $X_1(t)$ and $X_1'(t)$ (and $X_2(t)$ and $X_2'(t)$) is two, the diversity order between any two different matrices of the set $\{\mathbf{X}_0, \mathbf{X}_1, \mathbf{X}_2, \mathbf{X}_3\}$ is four.

The design of intra-block interleaving patterns includes two steps. The first step is to find permutation patterns in an STBC block, and the second step is to apply these patterns to all $N_T/4$ STBC blocks. Consider the first step. There are $4! = 24$ possible permutations within four columns of a 4 × 4 STBC block. If there are only two different elements between two distinct permutations, i.e., switching two elements of one permutation becomes the other, the transmit diversity order is only one. Hence, we should properly choose some patterns among the 24 possible permutations. We propose a new rule to obtain intra-block interleaving patterns as follows. First, list all 24 possible permutations: $\{[(1, 2, 3, 4), (1, 2, 4, 3)], [(1, 3, 2, 4), (1, 3, 4, 2)], [(1, 4, 2, 3), (1, 4, 3, 2)], [(2, 1, 3, 4), (2, 1, 4, 3)], [(2, 3, 1, 4), (2, 3, 4, 1)], [(2, 4, 1, 3), (2, 4, 3, 1)], [(3, 1, 2, 4), (3, 1, 4, 2)], [(3, 2, 1, 4), (3, 2, 4, 1)], [(3, 4, 1, 2), (3, 4, 2, 1)], [(4, 1, 2, 3), (4, 1, 3, 2)], [(4, 2, 1, 3), (4, 2, 3, 1)], [(4, 3, 1, 2), (4, 3, 2, 1)]\}$. For two patterns in the same bracket, because they only differ in the last two elements, only one of them can be used. First put $(1, 2, 3, 4)$ in the set of intra-block interleaving patterns, denoted by Π', and add patterns into Π' one by one. Each new element of Π' should satisfy the diversity order among all existing elements in Π'. First, $(1, 2, 4, 3)$ is abandoned since $(1, 2, 3, 4)$ is used. Then we put $(1, 3, 4, 2)$ into Π' because the number of different elements between $(1, 3, 2, 4)$ and $(1, 2, 3, 4)$ is only two. After that, $(1, 4, 3, 2)$ is not used due to the existence of $(1, 3, 4, 2)$, and so on. Finally, there are 12 intra-block interleaving patterns, which are $\Pi' = \{(1, 2, 3, 4), (1, 3, 4, 2), (1, 4, 2, 3), (2, 1, 4, 3), (2, 3, 1, 4), (2, 4, 3, 1), (3, 1, 2, 4), (3, 2, 4, 1), (3, 4, 1, 2), (4, 1, 3, 2), (4, 2, 1, 3), (4, 3, 2, 1)\}$. It can be observed that rotating the rightmost or leftmost three elements of any pattern in Π' results in another pattern in Π'. According to the design rule, the transmit diversity order is at least two between any two different patterns in Π'.

Then consider the second step, i.e., perform intra-block interleaving with the aid of Π' for $N_T \geq 8$. First, consider $N_T = 8$ for which there are two 4 × 4 STBC blocks in an STBC-DSM block. We must interleave two STBC blocks by the same elements in Π'. That is, one pattern in Π' is chosen, and the selected pattern is applied to two STBC blocks simultaneously.

The resulting Π is $\{(1, 2, 3, 4, 5, 6, 7, 8), (1, 3, 4, 2, 5, 7, 8, 6), (1, 4, 2, 3, 5, 8, 6, 7), (2, 1, 4, 3, 6, 5, 8, 7), (2, 3, 1, 4, 6, 7, 5, 8),$ (2,

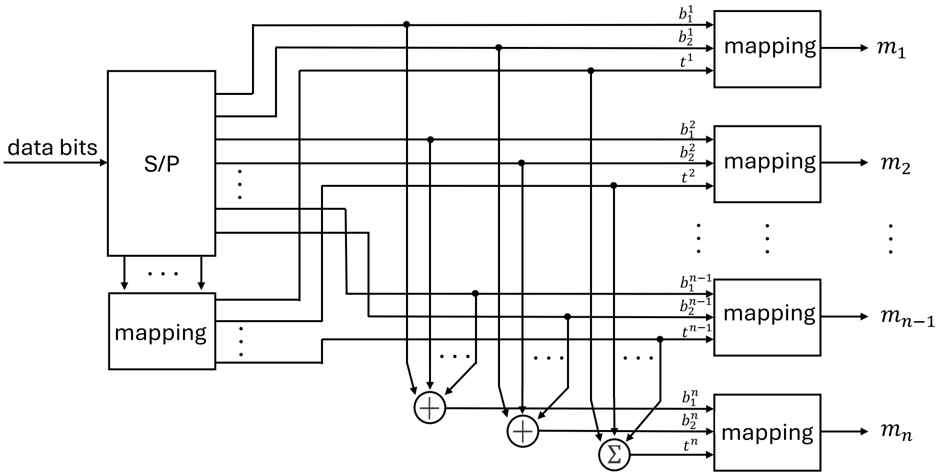

FIGURE 2. **The relation between data bits and intra-block interleaving patterns where the function Σ denotes the modulo-3 addition and $m_i = 1 + b_1^i + b_2^i \times 2 + t^i \times 4$ $i = 1, 2, \ldots, n$.**

4, 3, 1, 6, 8, 7, 5), (3, 1, 2, 4, 7, 5, 6, 8), (3, 2, 4, 1, 7, 6, 8, 5), (3, 4, 1, 2, 7, 8, 5, 6), (4, 1, 3, 2, 8, 5, 7, 6), (4, 2, 1, 3, 8, 6, 5, 7), (4, 3, 2, 1, 8, 7, 6, 5)}. Therefore, three data bits are mapped to one of the first eight patterns in Π. The transmit diversity order in each STBC block is two, so the transmit diversity order of HD-BE-STBC-DSM is four.

For $N_T \geq 12$, we can use the even-weight $(n, n-1, 2)$ block code to ensure that at least two STBC blocks use different intra-block interleaving where $n = N_T/4$. A possible and more straightforward method is that $3(n-1)$ data bits determine intra-block interleaving patterns of the first $n-1$ STBC blocks independently. That is, data bits b_1^1, b_2^1, b_3^1 select one from eight patterns in Π' for the first STBC block, and data bits b_1^2, b_2^2, b_3^2 choose one form eight patterns in Π' for the second STBC block, and so on. Subsequently, $n-1$ data bits $b_1^1, b_1^2, \ldots, b_1^{n-1}$ determine a codeword of the $(n, n-1, 2)$ code, $n-1$ data bits $b_2^1, b_2^2, \ldots, b_2^{n-1}$ form another codeword of the $(n, n-1, 2)$ code, and data bits $b_3^1, b_3^2, \ldots, b_3^{n-1}$ are inputs of the $(n, n-1, 2)$ code where $b_j^i \in \{0, 1\}$ for $i = 1, 2, \ldots, n-1$ and $j = 1, 2, 3$. Finally, the parity-check bits of the three $(n, n-1, 2)$ codewords are mapped to the last STBC block. However, it is a pity that four intra-block interleaving patterns are not utilized. Therefore, we propose a similar but more complicated scheme that uses all intra-block interleaving patterns to increase bandwidth efficiency in the following paragraph.

For $i \in \{1, 2, \ldots, n\}$ where $n = N_T/4$, we use b_1^i, b_2^i, and t^i to determine the intra-block interleaving pattern of the i-th STBC block where $b_1^i, b_2^i \in \{0, 1\}$ and $t^i \in \{0, 1, 2\}$. The intra-block interleaving pattern of the i-th STBC block is the $(1 + b_1^i + b_2^i \times 2 + t^i \times 4)$-th pattern in Π'. For the first $n-1$ STBC blocks, $b_1^1, b_2^1, b_1^2, \ldots, b_2^{n-1}$ are data bits and $t^1, t^2, \ldots, t^{n-1}$ are jointly mapped by other $\lfloor \log_2 3^{n-1} \rfloor$ data bits. Compared with the method described in the previous paragraph, additional $\lfloor \log_2 3^{n-1} \rfloor - n + 1$ data bits can be transmitted. Similarly, $(b_1^1, b_1^2, \ldots, b_1^{n-1})$ and $(b_2^1, b_2^2, \ldots, b_2^{n-1})$ are data bits of the $(n, n-1, 2)$ binary code, while $(t^1, t^2, \ldots, t^{n-1})$ is an input of the $(n, n-1, 2)$ ternary code. That is, $b_j^n = b_j^1 \oplus b_j^2 \oplus \cdots \oplus b_j^{n-1}$ for $j \in \{1, 2\}$ and $t^n = (t^1 + t^2 + \cdots + t^{n-1}) \mod 3$ determine the last STBC block. Therefore, for $N_T = 8, 12, \ldots,$, the spectral efficiency of the BE-STBC-DSM using the intra-block interleaving patterns is $\frac{3}{4}\log_2 M + \frac{1}{N_T}(\lfloor \log_2 (N_T/4)! \rfloor + N_T/2 - 2 + \lfloor \log_2 3^{N_T/4-1} \rfloor)$ bits per channel use. Figure 2 shows how to map data bits to intra-block interleaving patterns where the m_i-th intra-block interleaving pattern in Π' is used for the i-th STBC block.

For example, consider $N_T = 12$. In addition to four data bits $b_1^1, b_2^1, b_1^2, b_2^2$, three data bits are mapped to $(t^1, t^2) \in \{(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1)\}$, so there are totally $2^7 = 128$ intra-block interleaving patterns. The intra-block interleaving pattern of the last STBC block is decided by $b_j^3 = b_j^1 \oplus b_j^2$ where $j \in \{1, 2\}$ and $t^3 = (t^1 + t^2) \mod 3$.

Because any two distinct codewords of $(b_1^1, b_1^2, \ldots, b_1^n)$, $(b_2^1, b_2^2, \ldots, b_2^n)$, and $(t^1, t^2, \ldots, t^n)$ differ two elements at least, there are at least two STBC blocks whose transmit diversity order is two between any two different sequences of data bits. Consequently, the transmit diversity order of HD-BE-STBC-DSM is four.

IV. SEARCHES OF INTER-BLOCK INTERLEAVING PATTERNS

In addition to the intra-block interleaving, we utilize inter-block interleaving, which interleaves all symbols of $N_T/4$ STBC blocks, to further enhance bandwidth efficiency. We first search patterns for $N_T = 8$ and find patterns for $N_T = 12$ based on the patterns for $N_T = 8$. Patterns of inter-block interleaving for a larger value of N_T can be searched in a similar way. The initial set of all interleaving patterns $\boldsymbol{\pi}(t)$ is the set Π obtained by intra-block interleaving only, which means that the number of the initial set Π is 12 and 128 for $N_T = 8$ and 12, respectively. We add inter-block interleaving patterns one by one, and all intra-block interleaving are applied to each inter-block interleaving pattern. In other words, adding one inter-block interleaving pattern means adding 12 and 128 interleaving patterns of $\boldsymbol{\pi}(t)$ for $N_T = 8$ and 12, respectively. All new elements in Π should satisfy the diversity order among all existing elements in Π.

First consider the case of $N_T = 8$. In [10], we move the last three numbers of interleaving patterns cyclically to obtain other interleaving patterns with transmit diversity order of two. For the proposed scheme using the 4×4 STBC, we propose to shift the last five numbers of inter-block interleaving patterns cyclically to find other interleaving patterns. Doing it to $(1, 2, 3, 4, 5, 6, 7, 8)$ results in $(1, 2, 3, 8, 4, 5, 6, 7)$, $(1, 2, 3, 7, 8, 4, 5, 6)$, $(1, 2, 3, 6, 7, 8, 4, 5)$, and $(1, 2, 3, 5, 6, 7, 8, 4)$. The five inter-block interleaving patterns combined with 12 intra-block interleaving patterns result in 60 interleaving patterns. A computer program verifies that the transmit diversity order between any two different elements in Π is at least four.

Then we try all possible interleaving patterns one by one to increase the size of Π. If the transmit diversity order between the considered pattern and any element in Π is always not smaller than four, then add it into Π; otherwise, delete it and consider the next one. The considered inter-block interleaving patterns are $(1, 2, X, 3, 4, X, X, X)$, $(1, 2, X, 3, X, 4, X, X)$, $(1, 2, X, 3, X, X, 4, X)$, $(1, 2, X, 3, X, X, X, 4)$, $(1, X, 2, 3, 4, X, X, X)$, $(1, X, 2, 3, X, 4, X, X)$, $(1, X, 2, 3, X, X, 4, X)$, $(1, X, 2, 3, X, X, X, 4)$, $(1, X, X, 2, 3, 4, X, X)$, $(1, X, X, 2, 3, X, 4, X)$ $(1, X, X, 2, 3, X, X, 4)$, $(1, X, X, X, 2, 3, 4, X)$, $(1, X, X, X, 2, 3, X, 4)$ where "X" denotes 5, 6, 7, or 8. For each considered pattern, we try all 4! possibilities of (X, X, X, X) and all five patterns of shifting the last five numbers cyclically. That is, we test $4! \times 5 \times 13$ inter-block interleaving patterns one by one. After all testing, the final Π contains $192 = 12 \times 16$ elements, including 16 inter-block interleaving patterns which 12 intra-block interleaving patterns are applied to. The 16 inter-block interleaving patterns are $(1, 2, 3, 4, 5, 6, 7, 8)$, $(1, 2, 3, 8, 4, 5, 6, 7)$, $(1, 2, 3, 7, 8, 4, 5, 6)$, $(1, 2, 3, 6, 7, 8, 4, 5)$, $(1, 2, 3, 5, 6, 7, 8, 4)$, $(1, 2, 6, 3, 4, 7, 5, 8)$, $(1, 2, 6, 5, 8, 3, 4, 7)$, $(1, 2, 8, 3, 6, 4, 7, 5)$, $(1, 2, 8, 7, 5, 3, 6, 4)$, $(1, 5, 2, 3, 8, 7, 4, 6)$, $(1, 5, 2, 6, 3, 8, 7, 4)$, $(1, 6, 2, 8, 7, 5, 4, 3)$, $(1, 6, 5, 7, 2, 3, 4, 8)$, $(1, 6, 5, 4, 8, 7, 2, 3)$, $(1, 7, 6, 8, 2, 3, 5, 4)$, $(1, 7, 6, 5, 4, 8, 2, 3)$.

Because $2^7 < 192 < 2^8$, seven data bits can be transmitted via the interleaving patterns: four bits choose inter-block interleaving patterns while three bits select intra-block interleaving patterns. Due to $Q = 2$ and $R = 2^7$, the spectral efficiency is $1 + \frac{3}{4}\log_2 M$ bits per channel use, which is 2.5 bits/channel use for QPSK ($M = 4$).

We use the 16 inter-block interleaving patterns for $N_T = 8$ to find inter-block interleaving patterns for $N_T = 12$. For example, adding $(9, 10, 11, 12)$ to the end of the 16 inter-block interleaving patterns results in 16 inter-block interleaving patterns for $N_T = 12$. For each interleaving pattern for $N_T = 8$, the first number is always 1, and there are $8 \times 9 \times 10 \times 11 = 7920$ patterns of inserting 9, 10, 11, and 12 into the numbers 1 to 8. We test all 16×7920 patterns with 128 intra-block interleaving patterns. To reduce the space for showing interleaving patterns, we prefer that an inter-block interleaving pattern and its four related patterns obtained by cyclically shifting the last five numbers are all used patterns. With this property, it is sufficient to list 1/5 of all patterns. Therefore, during the search, if an inter-block interleaving pattern or its four related patterns combined with any intra-block interleaving pattern cannot satisfy the diversity order, this inter-block interleaving pattern and its four related patterns are not considered.

TABLE 1. Spectral efficiencies (bits/channel use) with $M = 4$ for FE-DSM-DR in [12], HD-STBC-DSM, and HD-BE-STBC-DSM.

	FE-DSM-DR	HD-STBC-DSM	HD-BE-STBC-DSM
$N_T = 8$	1.125	1.625	2.5
$N_T = 12$	1.083	1.667	3.0

By computer search, we obtain 595 inter-block interleaving patterns, which are 119 patterns and their related patterns. The 119 patterns are listed in the Appendix, where patterns generated from the same pattern of $N_T = 8$ are put in the same braces. For each DSM block, two data bits select $\mathbf{p}(t)$, seven data bits choose intra-block interleaving patterns, and nine data bits determine inter-block interleaving patterns. Therefore, the spectral efficiency is $1.5 + \frac{3}{4}\log_2 M$ bits/channel use, which is 3 bits/channel use for QPSK.

The STBC-DSM in [7] using the 4×4 STBC is called HD-STBC-DSM, which is HD-BE-STBC-DSM without interleaving. For the cases of $N_T = 8$ or 12 using QPSK, Table 1 lists the spectral efficiencies of FE-DSM-DR in [12], HD-STBC-DSM, and HD-BE-STBC-DSM using QPSK. STBC-RDSM [16] is not considered because its multi-block differential detection needs longer coherence time. The proposed HD-BE-STBC-DSM outperforms the other two schemes significantly. For $N_T = 12$, the value of HD-BE-STBC-DSM is approximately three and two times the values of FE-DSM-DR and HD-STBC-DSM, respectively.

V. SIMULATION RESULTS

The receivers of BE-STBC-DSM in [10] can be used for HD-BE-STBC-DSM. Similar to the analysis in [10], the low-complexity ML detection using decision feedback of the detected value of $\boldsymbol{\pi}(t-1)$, which is used in this paper's simulation, needs $14N_TN_RQRM^2$ real-valued multiplications for BE-STBC-DSM. The upper bound of the bit error probability for HD-BE-STBC-DSM can also be found in [10]. Nevertheless, this bound is too complicated (due to high data rates) to be plotted.

In all simulations, we use $N_R = 2$ and $M = 4$ as [10]. Simulation results of HD-STBC-DSM and HD-BE-STBC-DSM (with both intra-block and inter-block interleaving) for $N_T = 8$ are shown in Fig. 3. HD-BE-STBC-DSM using intra-block interleaving only (without inter-block interleaving), denoted by "HD-BE-STBC-DSM, intra", is also

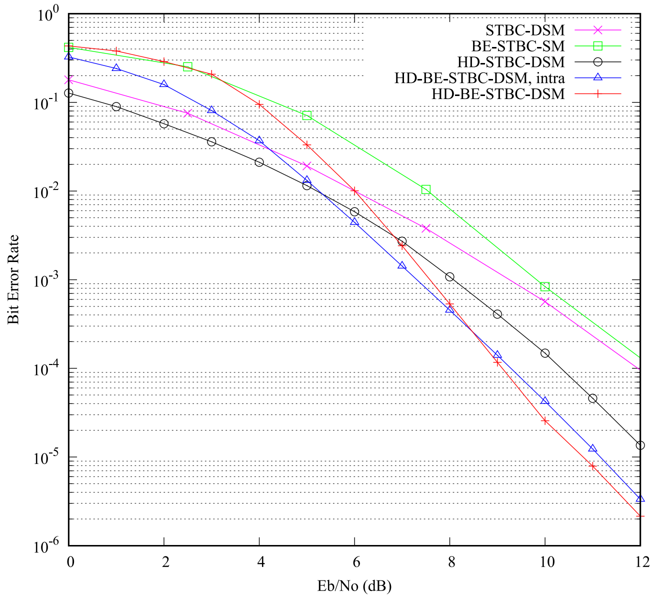

FIGURE 3. Simulation results of various schemes using QPSK for $N_T = 8$ and $N_R = 2$.

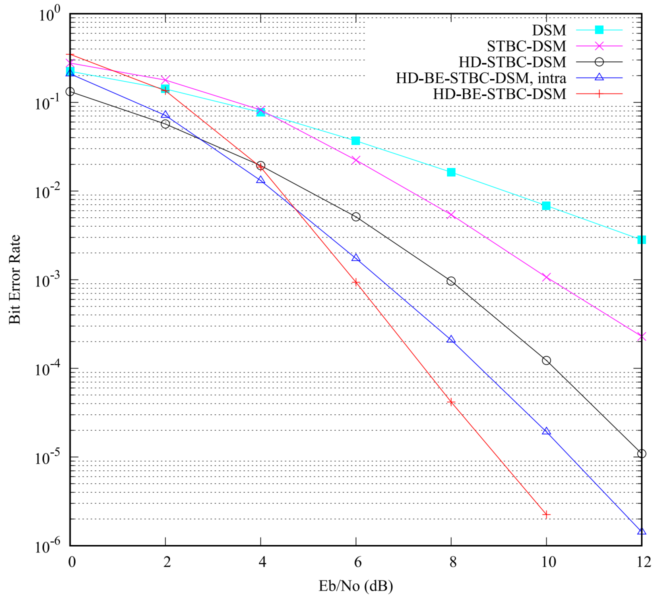

FIGURE 4. Simulation results of various schemes using QPSK for $N_T = 12$ and $N_R = 2$.

TABLE 2. Spectral efficiencies (bits/channel use) with $M = 4$ for DSM schemes used in the simulations, including STBC-DSM in [7], BE-STBC-DSM, and HD-BE-STBC-DSM with intra-block interleaving only.

	STBC-DSM	BE-STBC-DSM	HD-BE-STBC-DSM, intra
$N_T = 8$	2.5	3.375	2.0
$N_T = 12$	2.75	-	2.25

simulated. The lines in Fig. 3 are straight lines at high signal-to-noise ratios. According to the slopes between $E_b/N_0 = 10$ dB and $E_b/N_0 = 12$ dB, their diversity order exceeds 4 apparently. In addition, simulation results of STBC-DSM in [7] and BE-STBC-DSM in [10] using Alamouti's STBC are also plotted. Spectral efficiencies of the three additional schemes are shown in Table 2. Among three schemes with four transmit diversity order, HD-BE-STBC-DSM is the best, and HD-STBC-DSM is the worst at high SNRs. At the bit error rate of 10^{-4}, the gain of HD-BE-STBC-DSM over HD-STBC-DSM is roughly 1.25 dB. Compared with STBC-DSM in [7] whose transmit diversity order is two, HD-BE-STBC-DSM has the same spectral efficiency and offers approximately 2.82 dB gain at the bit error rate of 10^{-4}.

Fig. 4 presents simulation results of STBC-DSM in [7] using Alamouti's STBC, HD-STBC-DSM, HD-BE-STBC-DSM, and HD-BE-STBC-DSM using intra-block interleaving only for $N_T = 12$. The gain of HD-BE-STBC-DSM over HD-STBC-DSM at the bit error rate of 10^{-4} is roughly 2.75 dB. Compared with STBC-DSM in [7], HD-BE-STBC-DSM has higher spectral efficiency and provides more than 5 dB gain at the bit error rate of 2×10^{-4}. Besides, DSM in [3] with $N_T = 4$ and $N_R = 2$, which has the same spectral efficiency as HD-BE-STBC-DSM but only has one transmit diversity order, is also simulated and plotted in Fig. 4. The gap between DSM and HD-BE-STBC-DSM is huge.

VI. CONCLUSION

This paper proposes HD-BE-STBC-DSM, whose transmit diversity order is four. We propose a novel interleaving type, intra-block interleaving, and a new design method. Besides, we propose a search method for inter-block interleaving patterns. Compared with other schemes with the same diversity order, HD-BE-STBC-DSM is much more spectrally efficient. Besides, HD-BE-STBC-DSM provides better error performance at high SNRs than other STBC-DSM schemes.

APPENDIX

The 119 inter-block interleaving patterns for $N_T = 12$ are
{(1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12), (1, 2, 3, 4, 5, 10, 11, 6, 7, 8, 9, 12), (1, 2, 3, 10, 4, 5, 12, 6, 7, 8, 11, 9), (1, 2, 10, 3, 4, 11, 5, 6, 7, 8, 9, 12), (1, 2, 3, 11, 10, 4, 5, 6, 7, 8, 12, 9), (1, 10, 2, 3, 4, 5, 11, 6, 7, 12, 8, 9), (1, 10, 2, 3, 12, 4, 5, 6, 7, 9, 8, 11), (1, 2, 11, 10, 3, 4, 5, 6, 7, 9, 8, 12), (1, 2, 10, 3, 12, 4, 9, 5, 6, 7, 8, 11), (1, 11, 2, 10, 3, 4, 9, 5, 6, 7, 8, 12), (1, 2, 3, 9, 10, 12, 4, 5, 6, 7, 8, 11), (1, 2, 11, 3, 9, 10, 4, 5, 6, 7, 8, 12), (1, 2, 12, 11, 3, 9, 4, 5, 6, 7, 8, 10), (1, 10, 2, 12, 11, 3, 4, 5, 6, 7, 9, 8), (1, 2, 3, 12, 9, 11, 10, 4, 5, 6, 7, 8), (1, 10, 9, 2, 3, 12, 11, 4, 5, 6, 7, 8), (1, 9, 11, 2, 12, 10, 3, 4, 5, 6, 7, 8)}, {(1, 2, 3, 8, 4, 5, 6, 7, 9, 10, 11, 12), (1, 2, 11, 3, 8, 12, 9, 4, 5, 6, 7, 10), (1, 11, 2, 3, 10, 8, 12, 4, 5, 6, 7, 9), (1, 2, 9, 11, 3, 8, 12, 4, 5, 6, 7, 10), (1, 10, 2, 3, 12, 9, 8, 4, 5, 6, 7, 11), (1, 9, 2, 10, 3, 11, 8, 4, 5, 6, 7, 12), (1, 2, 9, 12, 10, 3, 8, 4, 5, 6, 7, 11), (1, 2, 3, 8, 10, 11, 9, 4, 5, 12, 6, 7), (1, 10, 12, 2, 3, 8, 11, 4, 5, 9, 6, 7)}, {(1, 2, 3, 7, 8, 4, 5, 6, 9, 10, 11, 12), (1, 2, 11, 3, 7, 8, 9, 4, 5, 12, 10, 6), (1, 11, 2, 3, 10, 7, 8, 4, 5, 12, 9, 6), (1, 12, 2, 3, 11, 7, 8, 4, 10, 9, 5, 6)}, {(1, 2, 3, 6, 7, 8, 4, 5, 9, 10, 11, 12), (1, 2, 3, 12, 6, 7, 8, 4, 5, 9, 10, 11), (1, 2, 11, 3, 6, 7, 8, 4, 9, 5, 12, 10)}, {(1, 2, 3, 5, 6, 7, 11, 8, 9, 10, 4, 12), (1, 2, 3, 11, 5, 9, 12, 6, 7, 8, 4, 10), (1, 12, 9, 2, 10, 3, 5, 6, 7, 8, 11, 4)},

{(1, 10, 2, 12, 6, 3, 11, 4, 7, 5, 9, 8), (1, 2, 6, 11, 3, 9, 12, 4, 7, 10, 5, 8), (1, 9, 2, 6, 3, 10, 12, 4, 7, 11, 5, 8), (1, 11, 2, 6, 10, 9, 3, 4, 7, 12, 5, 8), (1, 12, 2, 10, 11, 6, 3, 4, 7, 9, 5, 8)}, {(1, 2, 6, 5, 8, 3, 9, 4, 7, 10, 11, 12), (1, 2, 6, 5, 8, 11, 3, 4, 7, 9, 12, 10), (1, 2, 6, 5, 9, 8, 3, 4, 7, 12, 10, 11), (1, 2, 6, 5, 10, 8, 3, 4, 9, 7, 11, 12), (1, 2, 6, 10, 5, 8, 12, 3, 4, 7, 11, 9), (1, 2, 6, 5, 9, 10, 8, 3, 4, 7, 11, 12), (1, 2, 6, 12, 5, 11, 8, 3, 4, 7, 9, 10), (1, 10, 2, 6, 5, 12, 8, 3, 4, 7, 9, 11), (1, 2, 6, 11, 10, 5, 8, 3, 4, 7, 12, 9), (1, 2, 6, 11, 5, 8, 3, 4, 10, 9, 7, 12), (1, 2, 6, 5, 11, 8, 10, 3, 4, 12, 7, 9), (1, 10, 11, 2, 6, 5, 8, 3, 4, 12, 7, 9), (1, 2, 6, 5, 11, 12, 8, 3, 9, 4, 7, 10), (1, 2, 6, 10, 12, 5, 8, 3, 11, 4, 7, 9), (1, 11, 2, 6, 10, 5, 8, 3, 12, 4, 7, 9), (1, 10, 2, 9, 6, 5, 8, 3, 12, 4, 11, 7), (1, 2, 6, 11, 5, 12, 9, 8, 3, 4, 10, 7), (1, 10, 2, 6, 5, 9, 12, 8, 3, 4, 11, 7), (1, 11, 2, 6, 9, 10, 5, 8, 3, 4, 12, 7), (1, 11, 12, 2, 6, 9, 5, 8, 3, 4, 10, 7), (1, 10, 11, 9, 2, 6, 5, 8, 3, 4, 12, 7), (1, 2, 6, 5, 12, 8, 10, 3, 11, 9, 4, 7)}, {(1, 2, 8, 10, 11, 3, 9, 6, 4, 12, 7, 5)}, {(1, 2, 8, 7, 5, 11, 9, 3, 6, 4, 10, 12), (1, 2, 8, 10, 7, 11, 5, 3, 6, 9, 4, 12), (1, 2, 8, 12, 9, 10, 7, 5, 3, 6, 4, 11), (1, 9, 11, 2, 8, 10, 7, 5, 3, 12, 6, 4), (1, 9, 10, 12, 2, 8, 7, 5, 3, 11, 6, 4)}, {(1, 10, 5, 2, 3, 8, 7, 4, 6, 9, 11, 12), (1, 5, 10, 12, 2, 3, 8, 7, 4, 6, 11, 9), (1, 5, 10, 2, 3, 8, 7, 4, 9, 12, 6, 11), (1, 10, 11, 5, 2, 3, 8, 7, 4, 12, 6, 9), (1, 5, 2, 11, 10, 3, 8, 7, 4, 12, 9, 6), (1, 5, 2, 3, 8, 11, 12, 7, 10, 4, 9, 6), (1, 5, 2, 11, 3, 12, 8, 7, 9, 4, 10, 6), (1, 10, 5, 2, 3, 11, 8, 7, 9, 4, 12, 6), (1, 11, 5, 2, 3, 8, 12, 7, 9, 10, 4, 6), (1, 5, 9, 2, 11, 3, 8, 7, 10, 12, 4, 6), (1, 10, 5, 12, 2, 9, 3, 8, 11, 7, 4, 6), (1, 11, 9, 10, 5, 2, 3, 8, 12, 7, 4, 6)}, {(1, 5, 2, 6, 3, 10, 8, 7, 4, 9, 11, 12), (1, 5, 2, 6, 9, 3, 8, 7, 4, 11, 12, 10), (1, 5, 9, 2, 6, 3, 8, 7, 4, 10, 11, 12), (1, 10, 5, 2, 6, 3, 8, 7, 4, 11, 12, 9), (1, 10, 5, 11, 2, 6, 3, 8, 7, 4, 12, 9), (1, 5, 2, 6, 11, 3, 8, 7, 9, 10, 4, 12), (1, 5, 10, 2, 6, 12, 3, 8, 7, 9, 4, 11), (1, 11, 5, 2, 6, 9, 3, 8, 12, 7, 4, 10), (1, 12, 5, 9, 2, 6, 3, 8, 10, 7, 4, 11), (1, 5, 10, 2, 12, 6, 9, 3, 8, 7, 4, 11), (1, 5, 2, 11, 6, 3, 10, 8, 9, 7, 12, 4), (1, 5, 12, 2, 6, 3, 11, 8, 10, 7, 9, 4), (1, 5, 10, 2, 11, 6, 3, 8, 9, 7, 12, 4), (1, 5, 2, 10, 9, 6, 11, 3, 8, 7, 12, 4), (1, 11, 5, 2, 9, 6, 12, 3, 8, 7, 10, 4), (1, 12, 9, 5, 2, 6, 10, 3, 8, 7, 11, 4), (1, 10, 5, 12, 11, 2, 6, 3, 8, 7, 9, 4), (1, 5, 2, 9, 11, 6, 12, 3, 8, 10, 7, 4), (1, 10, 9, 5, 12, 2, 6, 3, 8, 11, 7, 4), (1, 5, 12, 2, 9, 6, 11, 3, 10, 8, 7, 4)}, {(1, 6, 5, 7, 2, 3, 4, 8, 9, 10, 11, 12), (1, 6, 9, 5, 7, 2, 3, 4, 8, 12, 10, 11), (1, 6, 5, 10, 7, 2, 12, 3, 4, 8, 11, 9), (1, 6, 5, 7, 9, 10, 2, 3, 4, 8, 11, 12), (1, 6, 5, 7, 2, 11, 9, 3, 4, 12, 8, 10), (1, 6, 5, 10, 7, 11, 2, 3, 4, 9, 8, 12), (1, 6, 10, 12, 5, 7, 2, 3, 11, 4, 8, 9), (1, 6, 10, 11, 5, 12, 7, 2, 3, 4, 8, 9), (1, 9, 10, 6, 5, 7, 2, 3, 4, 11, 12, 8), (1, 6, 5, 7, 10, 2, 12, 3, 11, 4, 9, 8), (1, 10, 6, 12, 5, 7, 11, 2, 3, 4, 9, 8), (1, 6, 10, 5, 7, 12, 9, 2, 11, 3, 4, 8)}, {(1, 6, 5, 10, 4, 11, 9, 8, 7, 2, 12, 3), (1, 6, 5, 12, 10, 9, 4, 8, 7, 2, 11, 3), (1, 6, 5, 4, 9, 10, 12, 8, 11, 7, 2, 3), (1, 6, 10, 5, 4, 12, 9, 8, 11, 7, 2, 3)}, {(1, 10, 11, 7, 12, 6, 9, 8, 2, 3, 5, 4)}, {(1, 10, 7, 6, 11, 5, 4, 8, 2, 12, 3, 9)}.

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